NASA-CR-194324

DEVELOPMENT OF AN UNSTEADY WAKE THEORY APPROPRIATE FOR AEROELASTIC ANALYSIS OF ROTORS IN HOVER AND FORWARD FLIGHT

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FINAL REPORT
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by

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Background

In 1987, we received a three-year grant from NASA Ames to develop a completely new kind of unsteady wake theory. This work was renewed in 1990 for a additional three-year period. However, due to the fact the Principal Investigator is moving from Georgia Tech to Washington University in St. Louis, the second phase has been terminated after one year at Georgia Tech; and a new Grant has been awarded at Washington University. Thus, this "Final Report" is actually a status report at the end of the fourth year of a six-year effort.

Personnel and Degrees

The following is a list of personnel who have worked on the project and their degrees, as applicable:

Person	Degree	Date Received(or Expected)
David A. Peters	(PI)	
Cheng Jian He	Ph.D.	August 1989
Ay Su	Ph.D.	December 1989
Yi Ren Wang	Ph.D.	(March 1992)
Bruce Nibbelink	Ph.D.	(June 1992)
Donizeti de Andrade*	Ph.D.	(June 1992)

* Supported by Brazilian Government

Publications

There are two types of publications that have resulted from this work. The first consists of those papers that deal with the development of the model. These reflect total or (at least) major funding from NASA and are listed below:

Peters, David A. and He, ChengJian, "A Closed-Form Unsteady Aerodynamic Theory for Lifting Rotors in Hover and Forward Flight", presented at the 43rd Annual National Forum of the American Helicopter Society, St. Louis, May 1987.

Peters, David A., "Modelling of Unsteady Aerodynamics for Rotary-Wing Aeroelasticity", Proceedings of the Sixth International Conference on Mathematical Modelling, St. Louis, August 4-7, 1987.

Peters, David A. and Su, Ay, "The Effect of an Unsteady Three-Dimensional Wake on Elastic Blade-Flapping Eigenvalues in Hover", Proceedings of the 45th Annual National Forum of the American Helicopter Society, Boston, May 22-24, 1989.

Peters, David A. and He, ChengJian, "Comparison of Measured Induced Velocities with Results from a Closed-Form Finite-State Wake Model in Forward Flight", Proceedings

of the 45th Annual National Forum of the American Helicopter Society, Boston, May 22-24, 1989.

Peters, David A., Boyd, David Doug and He, ChengJian, "A Finite-State Induced-Flow Model for Rotors in Hover and Forward Flight", *Journal of the American Helicopter Society*, Vol. 34, No. 4, October, 1989.

Peters, David A., He, ChengJian and Stumpf, Walter, "Combined Use of Finite-State Lift and Inflow Models for Rotorcraft Modelling", Workshop on Dynamics and Aeroelastic Stability Modelling of Rotorcraft Systems, Duke University, March 12-14, 1990.

Peters, David A. and Su, Ay, "Effect of Hidden Dynamic States on Floquet Eigenvalues", *Journal of the American Helicopter Society*, Vol. 35, No. 4, October, 1990.

Peters, David A. and Su, Ay, "An Integrated Airloads-Inflow Model for Use in Rotor Aeroelasticity and Control Analysis", Proceedings of the 47th Annual National Forum of the American Helicopter Society, Phoenix, May 6-8, 1991.

Peters, David A. and He, ChengJian, "Correlation of Measured Induced Velocities with a Finite-State Wake Model", *Journal of the American Helicopter Society*, Vol. 36(3), July, 1991.

Su, Ay, Yoo, Kyung M., and Peters, David A., "Extension and Validation of an Unsteady Wake Model for Rotors", *Journal of Aircraft*, to be published.

Peters, David A., and Su, Ay, "The Effect of an Unsteady, Three-Dimensional Wake on Elastic Blade-Flapping Eigenvalues in Hover", *Journal of the American Helicopter Society*, to be published.

Also, we have developed an extensive theoretical manual that has been delivered to the Technical Monitor for review. This will probably become a NASA document such as a CR or TR.

The second, type of publications consist of those in which the new wake model is used in other sponsored research as a tool. These reflect work done on grants other than this present one, but they represent applications of the theory. These are as follows:

Peters, David A. and He, ChengJian, "Optimization of Rotor Blades for Combined Structural, Dynamic, and Aerodynamic Properties", Proceedings of the Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, September 24-26, 1990.

Peters, David A. and He, ChengJian, "An Aeroelastic Analysis with a Generalized Dynamic Wake", Proceedings of the AHS International Technical Specialists' Meeting on Rotorcraft Basic Research, Atlanta, March 25-27, 1991.

Peters, David A. and He, ChengJian, "Integration of Dynamic, Aerodynamic, and Structural Optimization of Rotor Blades", NASA Interdisciplinary Office Optimization Workshop, April 11, 1991.

Finally, through private communications, our inflow code has been sent (by request) to the following users:

1. Sikorsky Helicopter Company
2. United Technologies Research Center
3. University of Maryland
4. NASA Langley Research Center
5. Georgia Tech Research Institute

Summary

It is rather interesting, at this point in the research effort, to summarize what we have accomplished over the past four years. By any standard of measure, results have far exceeded anything we imagined or proposed in our original presentation to NASA.

What we have done is to formulate a closed-form solution to the complete, three-dimensional, incompressible, potential flow equations for a rotor with arbitrary blade loadings. This implies that our solution is for a skewed cylindrical wake. This solution is obtained through an acceleration potential. However, the complicated integrals over the wake (from the rotor to the farfield) are found in a compact, closed form. Thus, no numerical wake integrals are required. The result is a set of ordinary differential equations in time for a finite number of aerodynamic states that describe the induced flow field at the rotor disk. Thus, the theory includes implicitly all effects of shed and trailing vorticity including tip relief, dynamic inflow, and conventional Theodorsen/Loewy unsteady aerodynamics.

Extensions and refinements to the theory are several. First, a nonlinear extension allows the massflow and wake skew angle to depend explicitly on the inflow states. This allows the theory to be well behaved even in hover, for which it reduces to classical momentum theory with Prandtl tip relief. Second, the theory can be written either in the nonrotating or the rotating coordinate system. The latter version eliminates periodic coefficients from dynamic analysis in hover. Third, the theory can be expressed in either real Fourier series or in Complex Fourier series. The latter can simplify frequency-response calculations.

A second aspect of our work is the fact that we have shown how our theory can be rigorously coupled to conventional airfoil theories to give a complete state-space unsteady aerodynamic theory. In general, the state-variable formulation allows aeroelasticity analyses to be done directly without the need for V-g or p-k iterations. We have made numerous applications of this type of theory to both rotary-wing and fixed-wing cases and have compared both with other theories and with experimental data. Major correlations include comparisons with:

1.) Army-Langley LDV measurements in forward flight
2.) George Tech Aerotech LDV measurements in hover
3.) Prandtl lifting-line theory for wings and blades
4.) Leowy function, Theodorsen function
5.) Panel method aerodynamic codes

Other results have been performed to determine the effect of inflow dynamics on systems for which no extensive data exists. These include:

1.) Flap-lag damping in hover
2.) Flap damping in forward flight
3.) Rotor response with wake and stall
4.) Rotor performance in forward flight.

Some of these are still being pursued.